SUBMARINE RADIATED NOISE FAR-FIELD BEAM PATTERNS FOR DISCRETE FREQUENCIES FROM NEAR-FIELD MEASUREMENTS

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THESIS

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by

Frederick Roberts Crawford

December 1975

Thesis Advisor: G. L. Sackman

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Submarine Radiated Noise Far-Field Beam Patterns for Discrete Frequencies from Near-Field Measurements		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis December 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Frederick Roberts Crawford		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE December 1975
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Near Field Far Field

Radiated Noise Submarine

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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the source. These assumptions and restrictions lead to a mathematical solution of the Helmholtz equation which is in the form of a Fourier transform. Near-field measurements on a horn speaker in an anechoic chamber were taken and the far-field beam pattern predicted by the model developed, using a simple computer program containing a Fourier transform routine. Computed beam patterns were in satisfactory agreement with measured far-field beam patterns, errors being concentrated in the outer side lobes from the acoustic axis. Problems which would be encountered in applying this model to at sea acoustic measurements are discussed. Methods for utilizing this model on an instrumented acoustic range to make underway radiated noise measurements on submarines are presented.

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by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING ACOUSTICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1975

ABSTRACT

A theoretical model was developed which can predict discrete frequency far-field radiation patterns of submerged submarines from near-field measurements. The model developed utilizes the Helmholtz integral equation and the assumptions of the DRL method of near-field measurements. The DRL working formula is further modified by using a plane surface of integration and restricting the far-field points of interest to a horizontal plane containing the source. These assumptions and restrictions lead to a mathematical solution of the Helmholtz equation which is in the form of a Fourier transform. Near-field measurements on a horn speaker in an anechoic chamber were taken and the far-field beam pattern predicted by the model developed, using a simple computer program containing a Fourier transform routine. Computed beam patterns were in satisfactory agreement with measured far-field beam patterns, errors being concentrated in the outer side lobes from the acoustic axis. Problems which would be encountered in applying this model to at sea acoustic measurements are discussed. Methods for utilizing this model on an instrumented acoustic range to make underway radiated noise measurements on submarines are presented.

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I. INTRODUCTION

Each submarine constructed in the United States is analyzed for radiated noise by an underway radiated noise survey. The purpose of this survey is described in Ship Acoustical Surveys, NAVSHIPS 0900-004-3000:

> The purpose of an underway radiated noise survey is easily stated in general terms. The total noise output of a ship or submarine while underway under standard operating conditions is to be determined in order to define the far-field radiated signature to determine detectability characteristics.

The radiated noise characteristics for a submarine may well determine its ability to survive in a hostile environment. Because the far-field radiated signatures are so important, it is worthwhile to know how a far-field signature is obtained and some of the difficulties in obtaining it.

The far-field is usually defined as the distance from a source beyond which the wavefronts are spherically diverging. For transducers a general criteria for far-field is [Bobber, 1970]:

$$x \geq D^2/\lambda \qquad (1.1)$$

where D is the maximum dimension of the radiating face of the transducer and λ is the wavelength of the radiated sound. Measurements made at a distance, x, as indicated in Equation (1.1) would be in the far-field. Now consider a submarine as a radiator and say that D^2 represents the cross sectional area from the beam. It is possible to approximate the

distance to the far-field for any given frequency. Applying Equation (1.1) to a frequency of 10 kHz and a submarine cross sectional area of 900 m^2, the calculated far-field would begin at 6000 m. Although this estimate of the inner edge of the far-field is conservatively high, it does illustrate that the far-field may be a considerable distance from the submarine radiating the noise. This distance can lead to difficulty in obtaining a free-field measurement. In practice, one must make measurements on submarines in the ocean, and greater distance to the far-field obliges one to contend with multi-path propagation of sound, ambient noise interference as well as attenuation of higher frequency signals. Because of the difficulty in obtaining free far-field measurements, the Navy became interested in obtaining far-field information on transducers by developing near-field measurement techniques. Bobber states the case for this interest in the chapter on "Near-Field Methods" in his book, Underwater Electroacoustic Measurements:

> It became obvious in the late 1950's that the small lake, pond and tank facilities of the Navy were running out of space (in wavelengths) as frequencies of a few kilohertz and large transducers were coming into use. If conventional far field measurements were to continue, very large bodies of water and very large and expensive facilities would be needed. The only alternative would be to devise measurement techniques which would change or eliminate the free-field far-field transducer proximity requirements. If, for example, one could make measurements in the near field or Fresnel zone of a transducer and extrapolate the results to conventional far-field patterns and response, a great savings in space and money could be realized.

In the early 1960's Horton, Innis and Baker of the Defense Research Laboratory of the University of Texas developed and tested a method of near-field measurement which has come to be known as the DRL method. This method was specifically aimed at the problems of measurements on transducers although the theory was more general. Could this type of near-field technique be applied to measurements of submarine radiated noise? If some of the difficulties of far-field measurement could be circumvented without creating a measurement or analysis procedure which is too complicated, then near-field would be a viable alternative to conventional far-field measurements on submarines. This paper discusses one possible method of near-field analysis and how it might practically be applied in collecting submarine radiated acoustic signatures.

II. THEORETICAL MODEL DEVELOPMENT

A simple model is a desirable goal, especially when the practical problems in making measurements at sea are considered. To develop a simple model an approach was selected utilizing the DRL near-field model [Horton and Innis, 1961]. The DRL method is based on the Helmholtz formula, Equation (2.1), and is illustrated in Figure 2.1. The formula states that if a sinusoidal or Fourier decomposable source is completely surrounded by a closed surface, S, and if the complex pressure, p(Q), and the pressure gradient, $\partial p(Q)/\partial n$, at every point on that surface is known, then the pressure at some point P external to the closed surface caused by the source can be calculated by the surface integral

$$p(P) = \left(\frac{1}{4\pi}\right)\iint_S \left\{ p(Q)\frac{\partial}{\partial n}\left(\frac{e^{jkr}}{r}\right) - \left(\frac{e^{jkr}}{r}\right)\frac{\partial}{\partial n}\left[\,p(Q)\,\right]\right\} ds, \qquad (2.1)$$

where p(Q) is the complex pressure at the point Q and n is the outward pointing normal to S at point Q. The DRL method is based on two key assumptions in the application of the Helmholtz integral, Equation (2.1). First, it is assumed that the wave propagation at the surface is approximately plane so that the approximation:

$$\frac{\partial\, p(Q)}{\partial n} \approx j\,k\,p(Q) \qquad (2.2)$$

is valid. The second assumption is that r is very large.

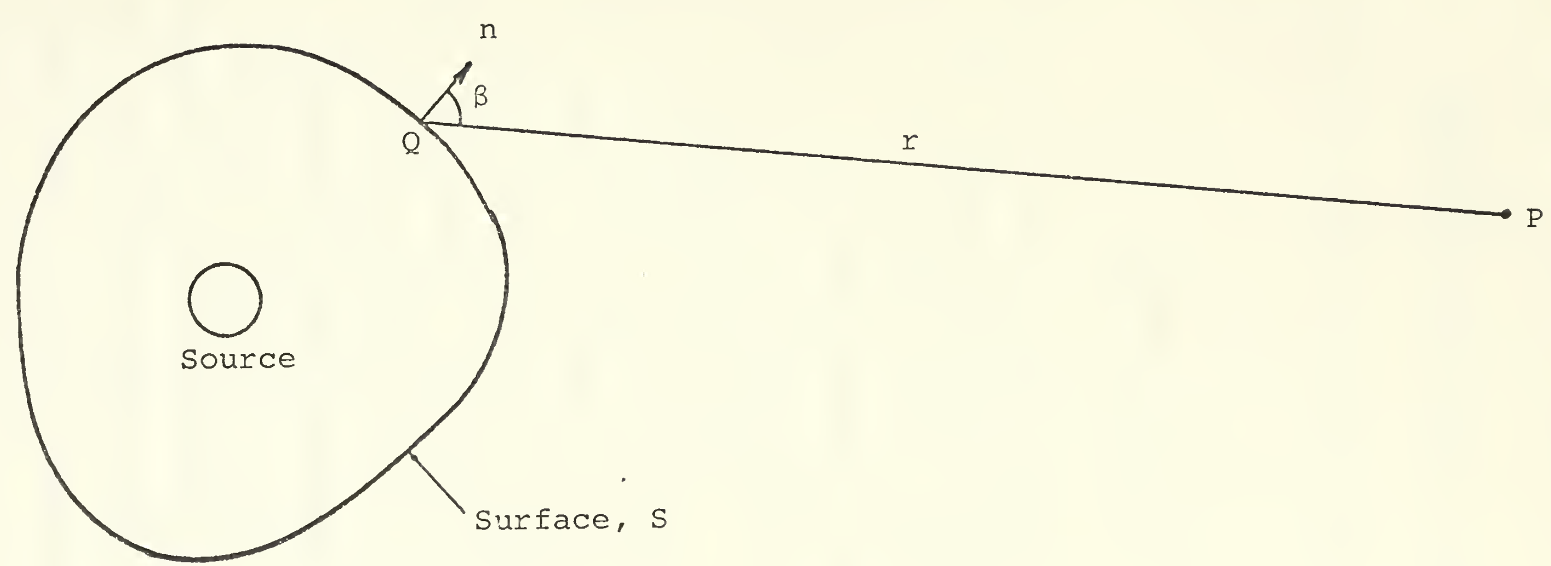

Fig. 2.1 Helmholtz Integral Relations. Pressure and pressure gradient over S are integrated by Eq. 2.1 to yield the far-field pressure at Point P. n is the outward pointing normal to the surface, S.

Since the far-field pressure, p(P), is desired, this is automatically valid and the following is a valid approximation:

$$\frac{\partial}{\partial n}\left(\frac{e^{jkr}}{r}\right) \approx \frac{jk}{r} e^{jkr} \frac{\partial r}{\partial n} = -j \frac{ke^{jkr}}{r} \cos\beta \qquad (2.3)$$

Substituting Equations (2.2) and (2.3) into Equation (2.1) yields:

$$p(P) = \left(\frac{-jk}{4\pi r}\right) \iint_S (1+\cos\beta) e^{jkr} p(Q) ds. \qquad (2.4)$$

This is the DRL method working formula. As it stands, it leads to some computational difficulties in calculating p(P). To simplify this formula and the necessary calculations as well as make a model which would be practically feasible for submarine radiated noise measurement, several simplifying choices and assumptions were made.

In the development of the working model a plane was utilized as the surface of integration. This plane is placed close to the source and allowed to extend to infinity in all directions. In practice, this plane is limited to a rectangular area such that the edges of the plane are sufficiently far from the source to have negligible pressure amplitude. Consider the plane oriented as shown in Figure 2.2. The plane determines a z axis perpendicular to the center of the plane. Now consider far-field points in a plane determined by the x and z axes. This is a reasonable restriction as primary interest in the target strength or beam pattern is usually in the horizontal plane containing the source. In

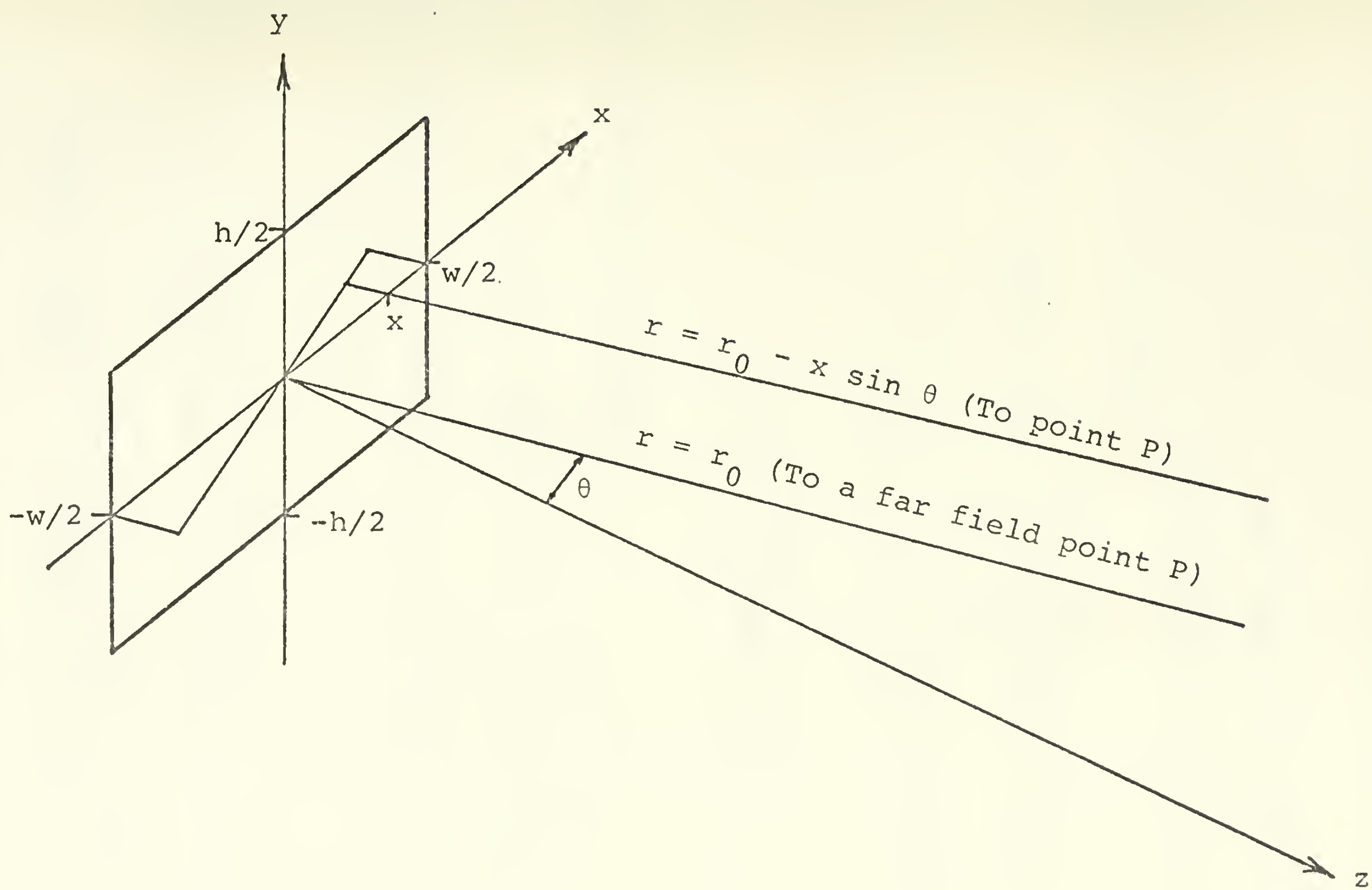

Fig 2.2 Surface of Integration. Rectangle in x-y plane is the surface of integration. Integration is performed to find far-field pressure p(P) at points in the x-z plane.

terms of the coordinates of Fig. 2.2, Equation (2.4) may be written

$$p(P) = \frac{-jk}{4\pi r} \int_{-w/2}^{w/2} \int_{-h/2}^{h/2} p(x,y,0)(1+\cos\Theta)e^{jkr}dydx. \quad (2.5)$$

Note that for the case we have chosen, the e^{jkr} is independent of y and the $(1+\cos\Theta)$ is independent of both x and y. Equation (2.5) then becomes

$$p(P) = \frac{-jk}{4\pi r}(1+\cos\Theta) \int_{-w/2}^{w/2} e^{jkr} \int_{-h/2}^{h/2} p(x,y,0)dydx. \quad (2.6)$$

Performing the integration in the y direction let the result be expressed as:

$$p(x) = \int_{-h/2}^{h/2} p(x,y,0)dy \quad (2.7)$$

Now equation 2.6 becomes:

$$p(P) = \frac{-jk}{4\pi r}(1+\cos\Theta) \int_{-w/2}^{w/2} p(x)\ e^{jkr}dx. \quad (2.8)$$

Note that r is a function of x, as shown in Fig. 2.2, so that the substitution

$$r = r_0 - x \sin\Theta$$

can be made. This simplifies Equation (2.8) to:

$$p(P) = \frac{-jk}{4\pi r_0}\ e^{jkr_0}(1+\cos\Theta) \int_{-w/2}^{w/2} p(x)e^{-jkx\sin\Theta}dx. \quad (2.9)$$

Now remember $k = \frac{2\pi}{\lambda}$ and let $s = \sin\Theta/\lambda$. This leads to:

$$p(P) = \left[\frac{-jk}{4\pi r_0} e^{jkr_0}\right] (1+\cos\Theta) \int_{-w/2}^{w/2} p(x) e^{-j2\pi s x\Theta} dx. \quad (2.10)$$

Note that the integral portion of Equation (2.10) is of the form of a Fourier transform:

$$D(s) = \int_{-w/2}^{w/2} p(x) e^{-j2\pi s x} dx = D\left(\frac{\sin\Theta}{\lambda}\right) = F(\Theta) \quad (2.11)$$

Equation (2.10) can be separated into two parts:

$$p(P) = [A(r)][B(\Theta)] \quad (2.12)$$

where

$$A(r) = \frac{-jk}{4\pi r_0} e^{jkr_0} \quad (2.13)$$

which is an amplitude and phase term dependent only on range and where

$$B(\Theta) = (1+\cos\Theta) \int_{-w/2}^{w/2} p(x) e^{-j2\pi s x} dx. \quad (2.14)$$

Equation (2.14) can be written with substitution from Equation (2.11) as:

$$B(\Theta) = (1+\cos\Theta)\ D(s) = (1+\cos\Theta)\ F(\Theta). \quad (2.15)$$

Equation (2.11) shows the Fourier transform pair relation between $p(x)$ and $D(s)$.

Consider the complex function $p(x)$. Recall that it was obtained mathematically by integrating over the plane of Fig. 2.2 in the vertical direction. This is mathematically shown by Equation (2.7). If complex pressure measurements in the x-y plane of Fig. 2.2 are made using a line hydrophone oriented

in the vertical (y) direction, then the line hydrophone output will be the function p(x) due to the integrating effect of the hydrophone. Once this function has been recorded as a complex quantity, it is only a matter of a Fourier transform computation and simple mathematics to obtain the far-field beam pattern, $B(\Theta)$, or the complex pressure at any far-field point, p(P). It should be noted, however, that this model cannot accurately predict the patterns as you approach 90° from the z axis of Fig. 2.2. An accurate description of the far-field near the $\pm$ 90° directions can be obtained by integration over y-z planes placed between the source and the far-field points in the +x and -x directions.

III. EXPERIMENTAL RESULTS USING THE PLANE MODEL

To validate the model described in Section II, far-field and near-field measurements were made on a horn speaker in an anechoic chamber. The objective was to actually measure the far-field beam pattern for the horn, then to take the necessary measurements in the near-field to be able to predict the far-field beam pattern. This was accomplished as described in the following paragraphs.

A. FAR-FIELD MEASUREMENT

The measurement of the normalized far-field beam pattern was made using the experimental setup shown in Fig. 3.1. A wave analyzer was used to generate a 5000 Hz. tone which was amplified and applied to the horn speaker. The microphone was placed in the far-field at R = 5.73 m. The microphone output was fed back through the wave analyzer which output a dc level proportional to the input amplitude. This dc output was applied to the y-axis of an x-y plotter. The dc position information from the horn rotator was fed into the x-axis of the plotter. The normalized amplitude versus angular position measured is shown on Fig. 3.2. This was the actual far-field beam pattern which was to be compared with that to be predicted by using near-field measurements and the plane model discussed in Section II.

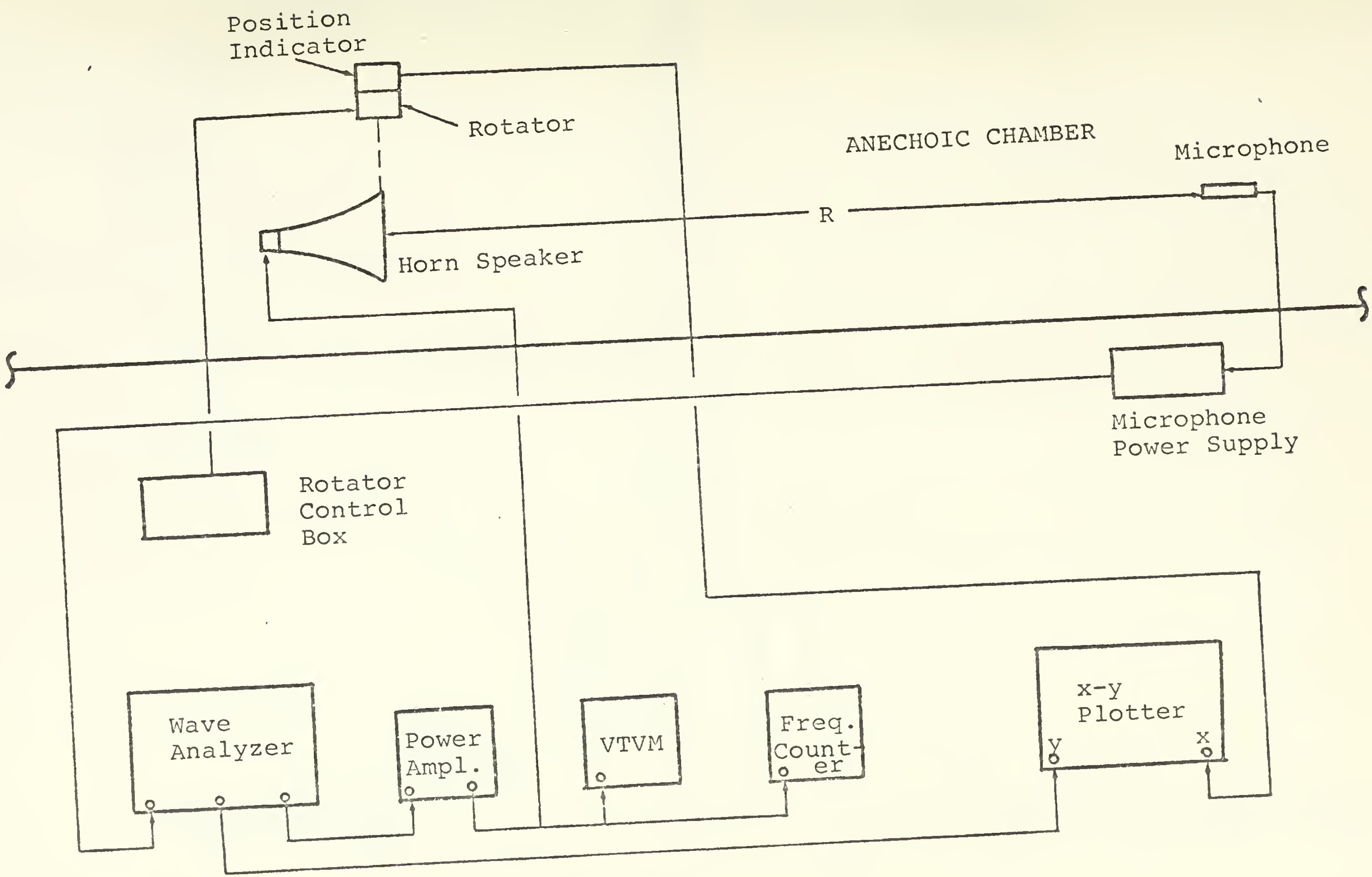

Fig. 3.1 Far-Field Beam Pattern Measurement Setup. Pressure amplitude at R = 5.73m, in the far field, was plotted vs. angle.

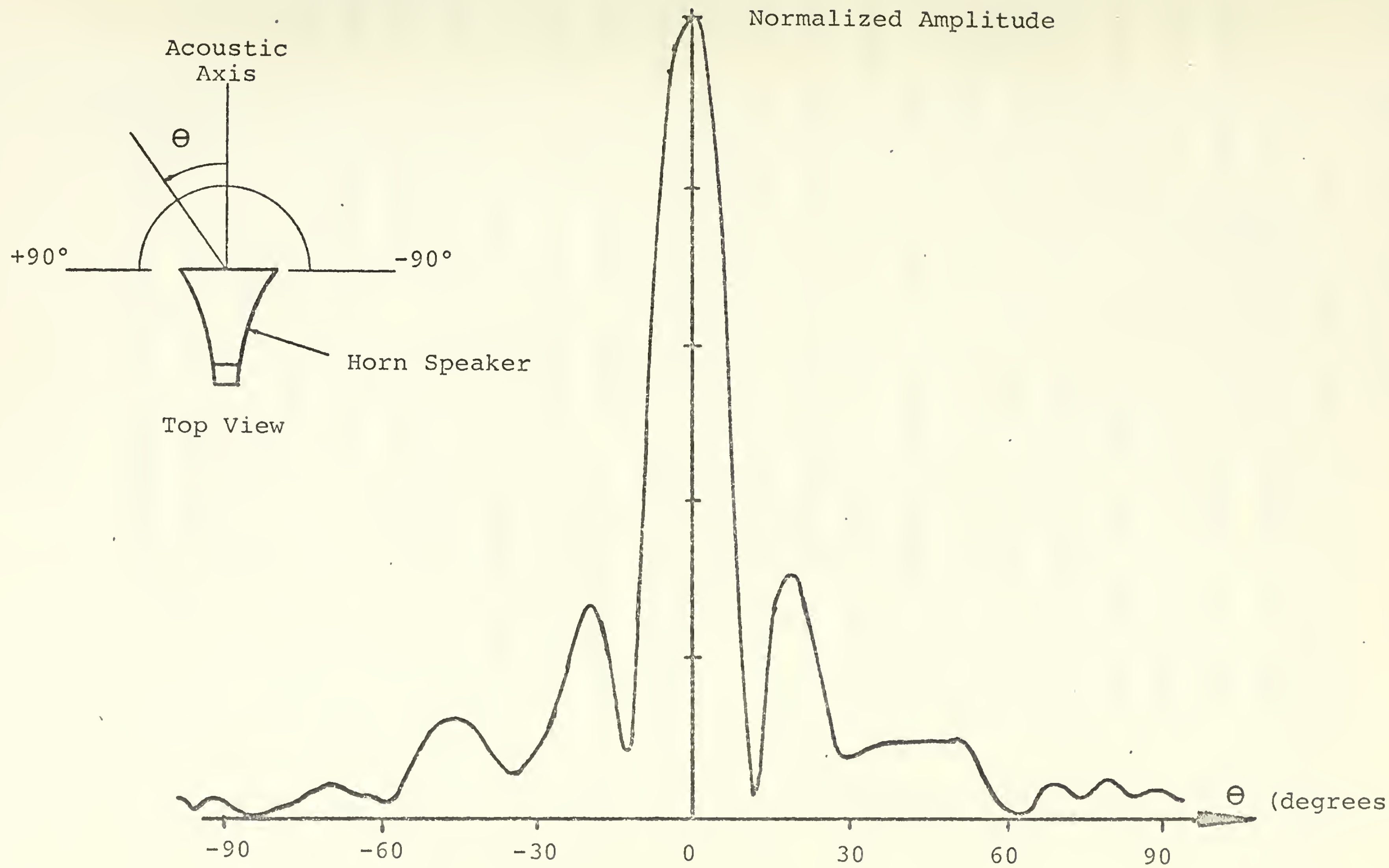

Fig. 3.2 Measured Far Field Beam Pattern - Horn Speaker

B. NEAR-FIELD MEASUREMENT

The model for near-field acoustic measurements described in Section II was developed assuming that when the pressure measurements over the plane surface were taken, they would be made with a vertically oriented line hydrophone. A line microphone with which to make these measurements was not available. Instead, a single microphone was used and measurements were made in the horizontal direction in the plane of integration at seven (7) separate vertical levels. Figure 3.3 shows the plane of integration and how it was sampled by levels. The plane surface on which the pressure measurements were made was positioned perpendicular to the acoustic axis and 2 cm. from the plane containing the mouth of the speaker. The microphone was mounted rigidly below a carriage which moved horizontally above the speaker. The physical arrangement in the anechoic chamber and test equipment schematic for making the near-field pressure measurements is depicted in Fig. 3.4. At each of the seven levels, shown in Fig. 3.3, two runs were made. The first measured and recorded relative pressure amplitude. The second measured and recorded phase angle referenced to the speaker driver. All amplitude measurements were normalized to the maximum amplitude found on level 4. A graph of normalized amplitude and relative phase versus position for each level was recorded. Figure 3.5 is the near-field data recorded for the center level of Fig. 3.3.

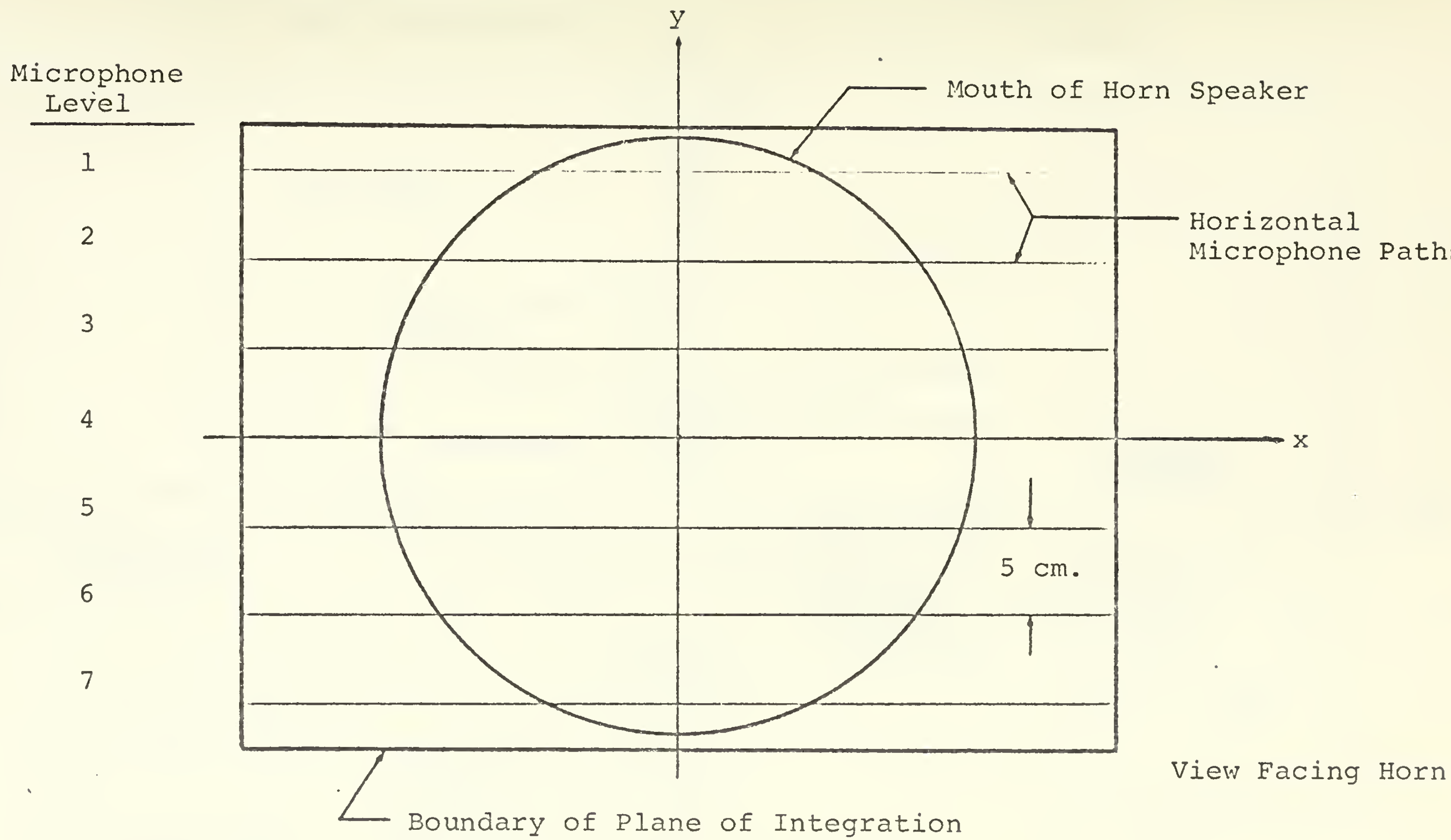

Fig. 3.3 Near-Field Plane Surface of Integration

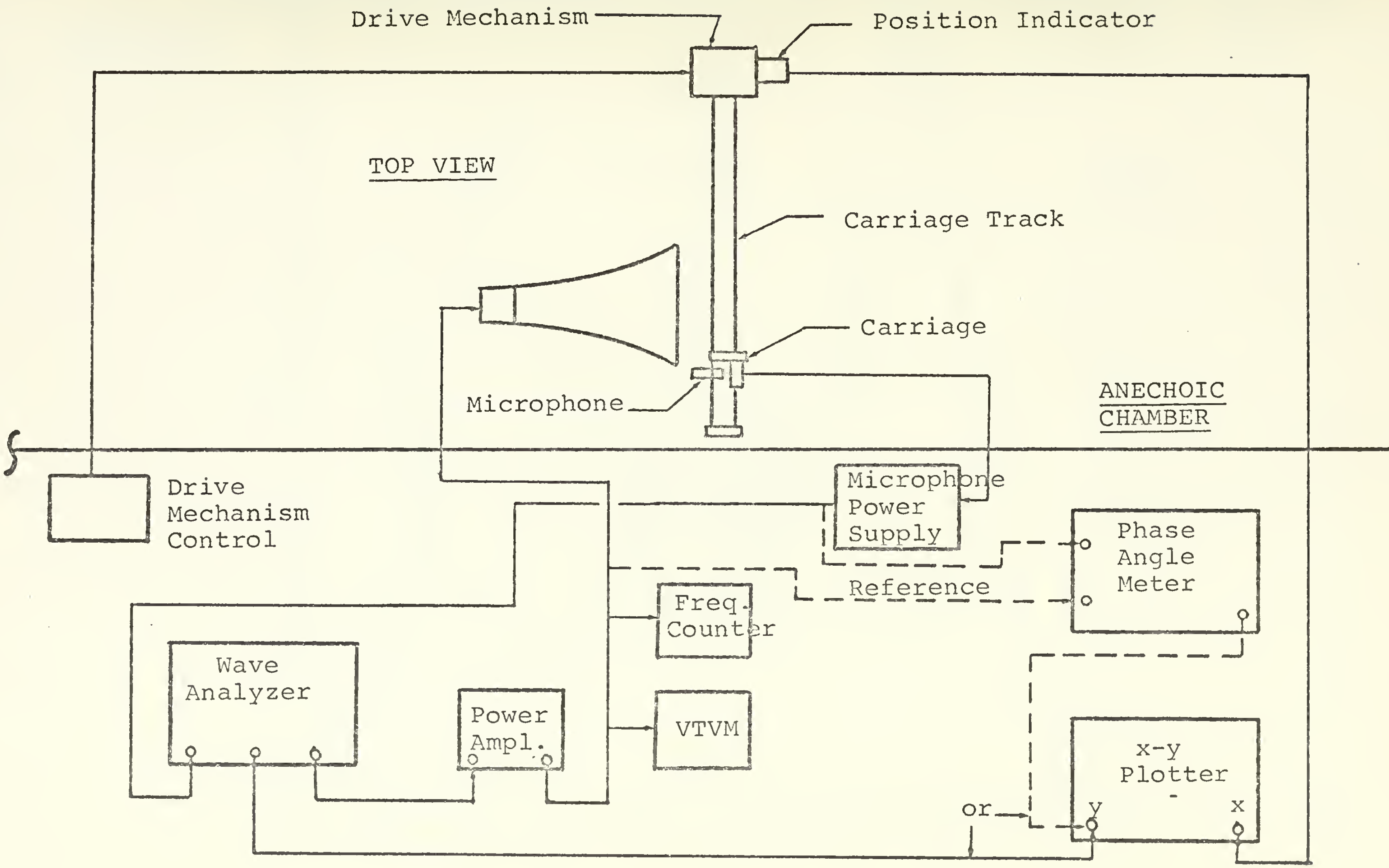

FIG. 3.4 Near Field Data Measurement Equipment

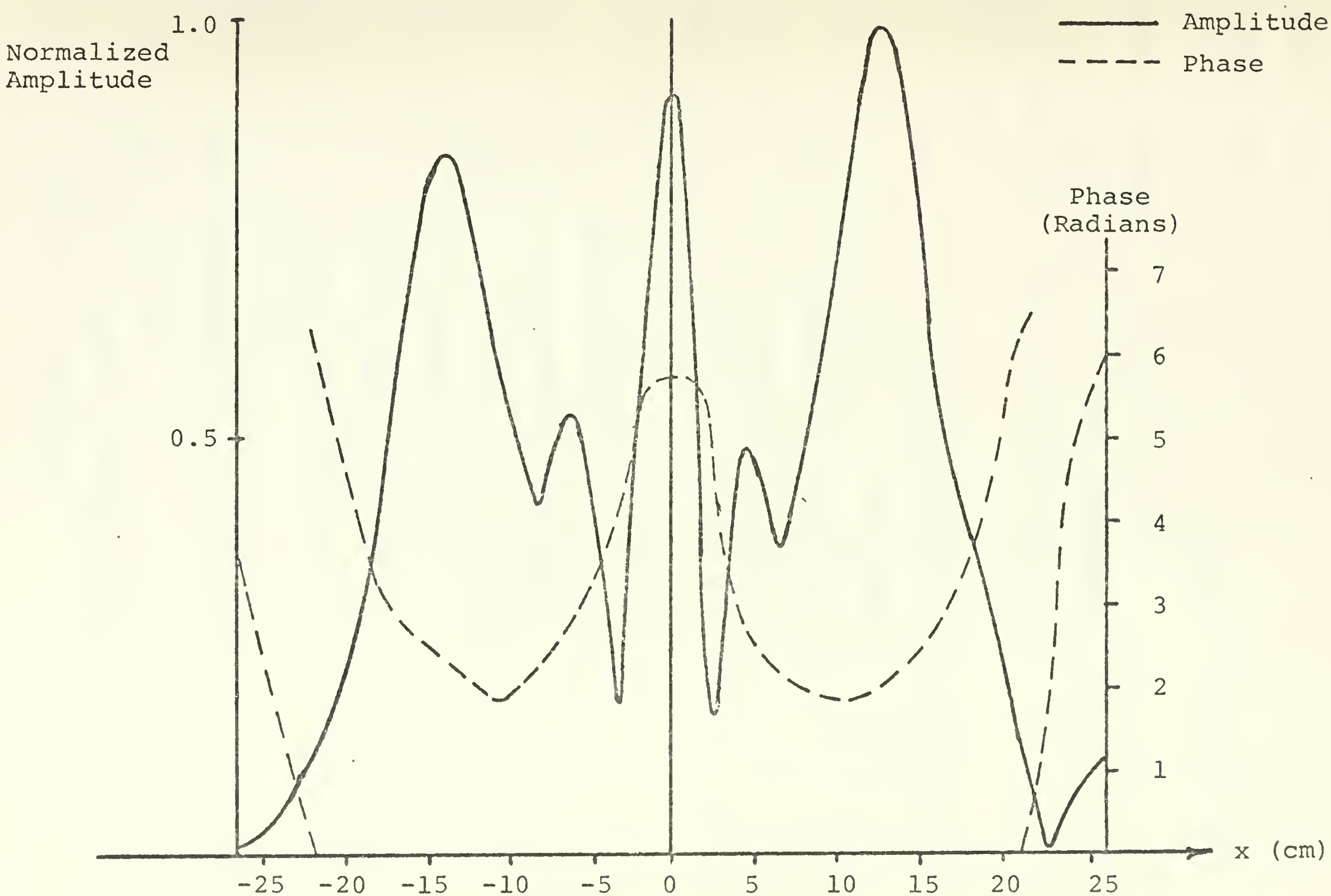

Fig. 3.5 Normalized Complex Pressure - Level 4 of Fig. 3.3.

C. NEAR-FIELD DATA PROCESSING

The data collected as described in subsection B above was processed using an IBM 360 computer program in Fortran IV language with library subroutines for Fourier transform and graphical output. The logical sequence of processing in the computer program is described below:

1. Complex pressure data points were input in magnitude and phase form. Seven levels of data were input each with 41 data points.

2. Each data point was converted into rectangular complex number form (Required form for Fortran IV language).

3. Complex pressures from all levels at each horizontal point were summed to simulate the integration of a line hydrophone and to form the complex pressure function p(x). [See Equation (2.7)].

4. The complex pressure p(x) was input as a vector matrix to the International Mathematical and Statistical Library (IMSL) subroutine, FFTP, to compute the Fourier transform. [See Equation (2.11)]

5. The Fourier transform output of the subroutine, D(s), is converted to $B(\Theta)$ and normalized to $B(\Theta)$ maximum value. [See Equation (2.14)]

6. The normalized function $B(\Theta)$ is output to the plotter by the DRAW routine.

The complete computer program used for processing the data is included as Appendix A.

D. RESULTS FROM NEAR-FIELD PLANE MODEL

The beam pattern output from the computer program is shown on Fig. 3.6. The actual measured far-field beam pattern is also shown for comparison on Fig. 3.6. Note that the agreement between the predicted and the measured beam patterns is quite good out to about $\pm$ 30 degrees. Beyond that point the agreement is fair. The absence of fine structure in the computed beam pattern is probably due to the spacing between the vertical samples in the near-field measurement (See Fig. 3.3). Note that the spacing here was 5 cm. which is 72 percent of a wavelength at the 5000 Hz experimental frequency. This spacing could be reduced to preserve the fine structure of the near-field and allow the model to predict the finer structure of the far-field pattern. If a continuous line microphone had been used as the model assumed, the vertical sampling distance would not have been an issue. However, the number and spacing of elements in a vertical line array should be considered. In spite of the deviations in fine structure, the experimental results do validate the model developed in Section II. The computer program is also noteworthy because it is not complicated. Most computers have or can easily be programmed to have simple Fourier transform routines. This makes the practical computations based on the near-field measurements less time consuming both in programming and in execution.

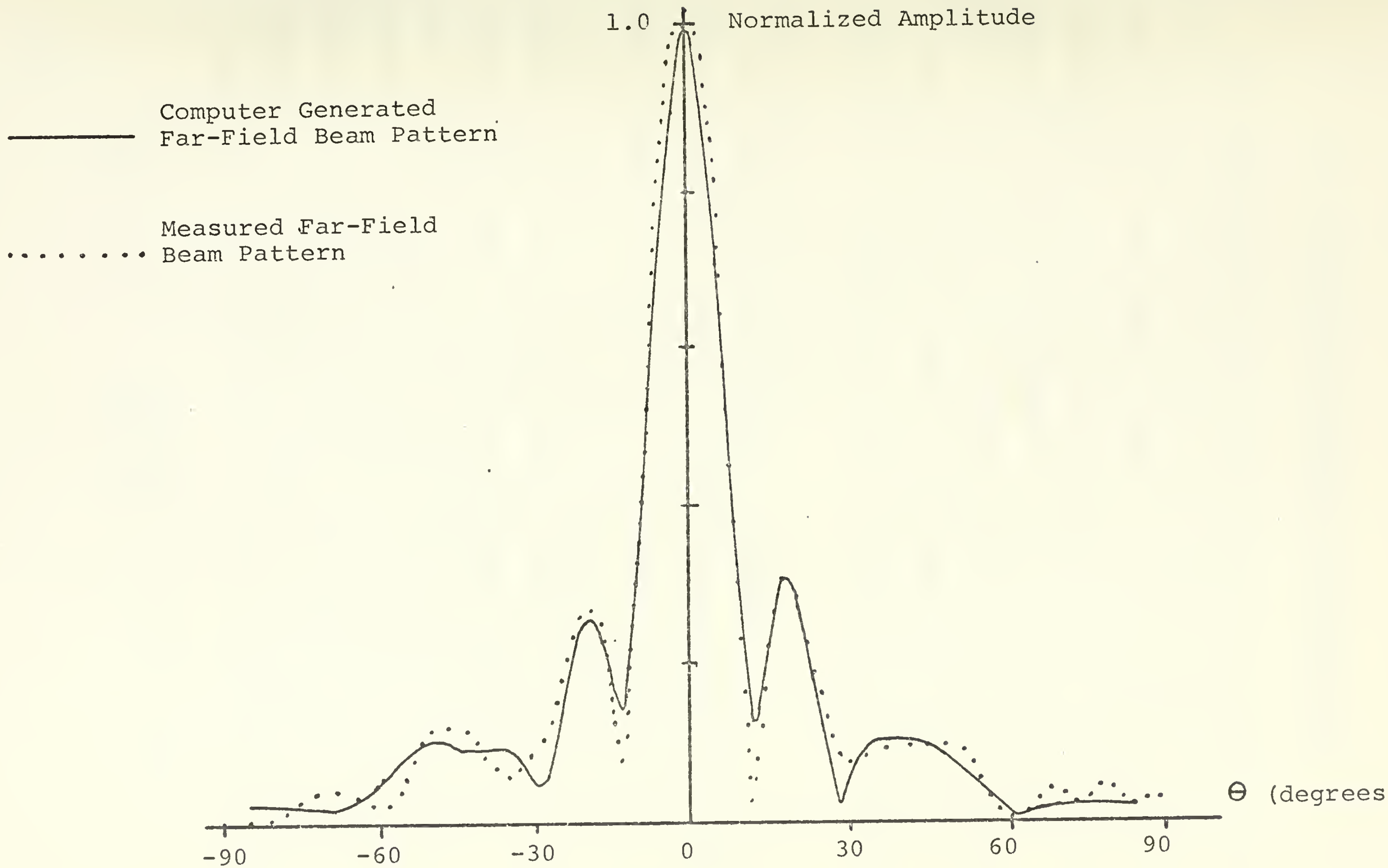

Fig. 3.6 Computed and Measured Far-Field Beam Pattern - Horn Speaker

IV. IN-SITU MEASUREMENT CONSIDERATIONS

The measurements described in Section III were all made in air in an anechoic chamber to simulate free-field measurements. This technique was used to validate the model while avoiding the necessity of considering several factors which arise when making measurements in an at-sea environment. This section discussed these factors and how they may be considered in applying the plane model or why they may reasonably be neglected in applying this model to in-situ measurements.

A. DOPPLER CONSIDERATIONS

For the measurements taken in Section III, the velocity of the microphone moving in front of the speaker was relatively slow (5.4×10^{-3} m/s) creating a maximum Doppler shift of only .077 Hz. This was actually so small a shift in frequency that the received frequency was still well within the narrow band width of the wave analyzer (See Fig. 3.4). For the case where an in-situ measurement is made with the line hydrophone fixed and the source of interest (a submerged submarine) moving by the array, the Doppler shift cannot be neglected. For example, a submarine moving past the array at a speed of 6 KTS would cause a maximum Doppler shift of:

$$\Delta f_d = (v_s/C)f = \left(\frac{3.08\ \text{m/s}}{1500\ \text{m/s}}\right) 20{,}000\ \text{Hz} = 41\ \text{Hz},$$

where

v_s - Velocity of the ship in m/s

C - Speed of sound in sea water and

f - Highest frequency of interest in the band of analysis.

This is of course too great a shift to be neglected.

The most practical approach to Doppler correction is correction of collected analog data before any further processing occurs. One technique for Doppler correction is currently utilized in the Torpedo Noise Acquisition and Analysis System (TNAAS) at the Naval Torpedo Station, Keyport, Washington. This system of Doppler correction, more completely described in "U. S. Torpedo Radiated Noise Measurement" [Rottler, 1973], is basicly an open loop Doopler correction system. The correction is determined by geometry and range rate derived from position information from the instrumented acoustic range. The hydrophone-target relative positions are calculated by digital computer and a digital correction signal is generated. This signal is then used to vary the drive speed of the magnetic tape playback equipment playing the acoustic data into the analysis equipment. This technique is currently in use and is advantageous if measurements are to be made on an instrumented acoustic range with this capability.

An alternate technique for obtaining Doppler correction when acoustic range data is not available utilizes a pilot tone sent by a transducer on the vessel being measured. The tone is generated by a stable oscillator carried on the submarine and transmitted by a specially calibrated transducer installed near the keel of the submarine. This tone is set

at a frequency near the high end of the analysis band at a point in the frequency spectrum which does not interfere with any discrete radiated frequencies. When the tape is analyzed, the pilot tone from a local oscillator is compared to the tone received on the tape. The Doppler shift detected on the tape would be used as an error signal to vary the drive speed of the tape as it is analyzed. This closed loop concept is illustrated in block diagram form on Fig. 4.1.

B. SURFACE/BOTTOM REFLECTIONS

The model described in Section II is based on free-field measurements. In practice, of course, there are no places where acoustic measurements can be made on a submarine that are truly free-field. How then can we take near-field measurements without having to consider the air-sea interface and the sea-bottom interface acoustic reflections? The most practical solution is to remove these boundaries as far as possible from the location where the measurements are actually made. Figure 4.2 illustrates a hydrophone location relative to the surface which would allow the direct path sound to be much more intense than the surface reflected path. In the figure the dotted box shows the surface of integration for the complex near-field pressure. Note that the direct path from any point on the submarine to any point on the plane surface is smaller than the reflected path by at least a factor of two. This will keep the amplitude of the potentially interfering surface reflections low enough to be neglected. If the measurement site chosen is 320 m. in depth or more and

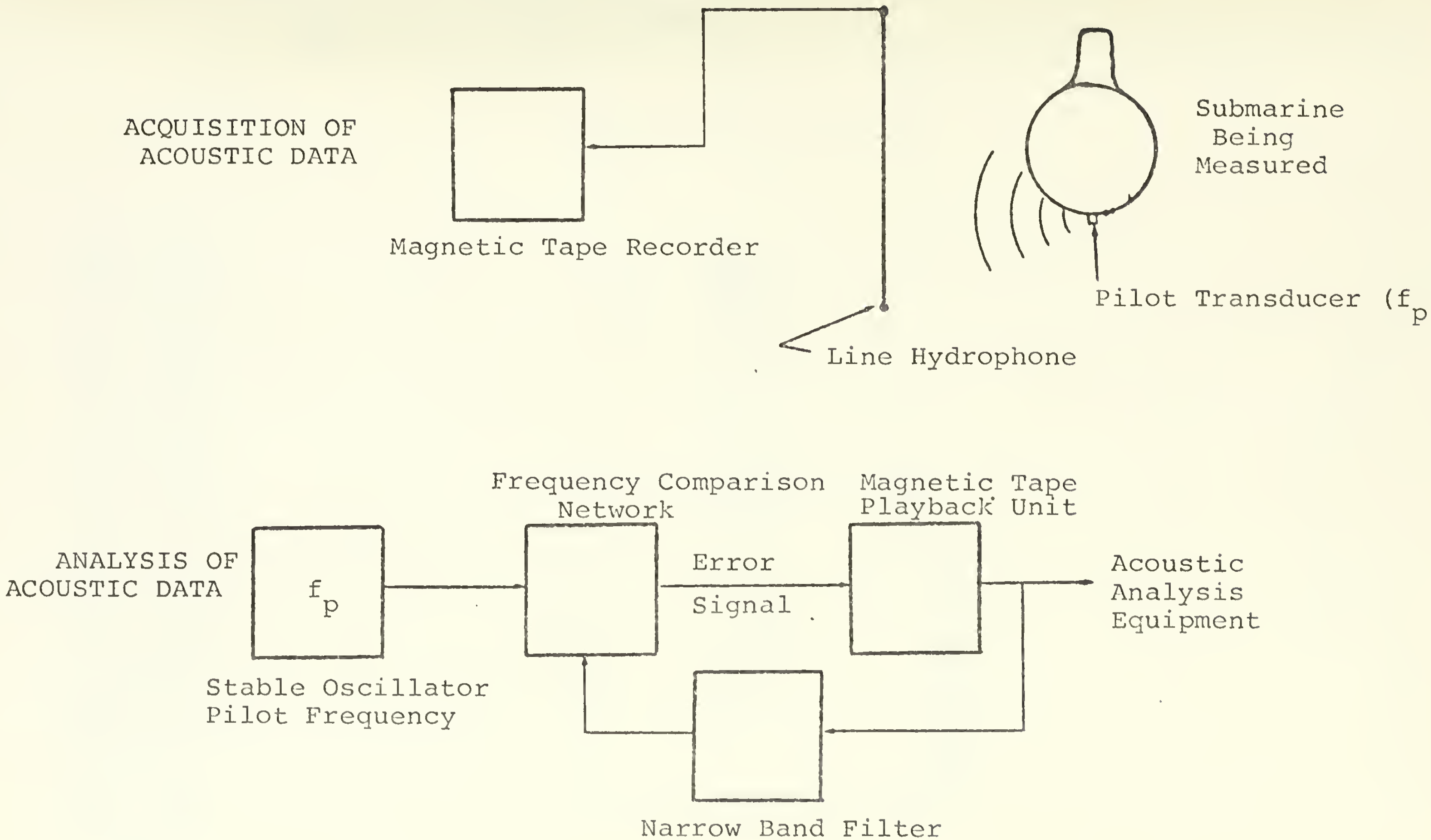

Fig. 4.1 Closed Loop Doppler Compensation System - Pilot transducers high frequency signal from tape is compared with actual pilot frequency to generate tape speed error signal.

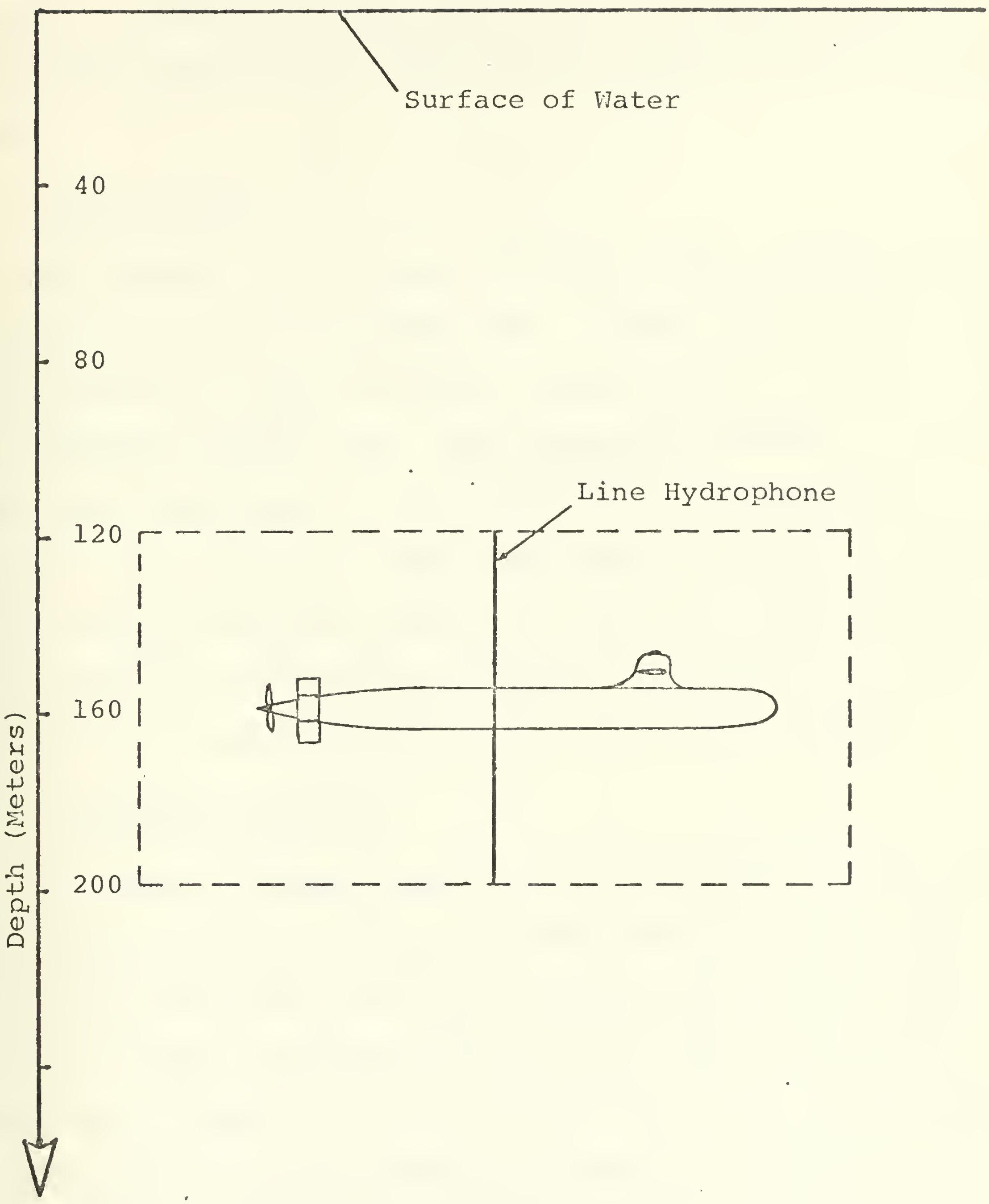

Fig. 4.2 Submarine Hydrophone Arrangement. Submerged submarine is driving by the line hydrophone array. The dotted box shows the surface (relative to the submarine) over which the complex pressure field will be integrated. Submarine-hydrophone CPA - 20 m.

has a lossy bottom then the location of the hydrophones shown in Fig. 4.2 would be satisfactory from the standpoint of minimizing interference from bottom reflected acoustic energy also.

C. AMBIENT NOISE

The ambient noise in most locations where acoustic measurements are made is already low. A Naval Sea Systems Command requirement for making underway radiated noise surveys, stated in NAVSHIPS 0900-004-3000, Ship Acoustical Surveys, is that the noise background be sea state limited to less than a Knudsen sea state two. This requirement for far-field measurements would more than satisfy the need for a quiet background for taking near-field measurements, so a different or more restrictive background noise limit need not be applied.

D. HYDROPHONE MOVEMENT

In order to obtain accurate near-field measurements as the submarine moves by the vertical array, the array needs to be fixed and stable. For this reason, dangling the hydrophone from the listening ship does not seem to be a good solution. Figure 4.3 shows a method of fixing the hydrophone which would avoid the coupling of sea surface motion to the hydrophone through the suspension cable. Here the array is held vertical by a float secured to the top of the array. The bottom of the array is secured to a downhaul cable which is fed through a downhaul eye. The cable is attached to the downhaul eye by a catch which can be released by the listening

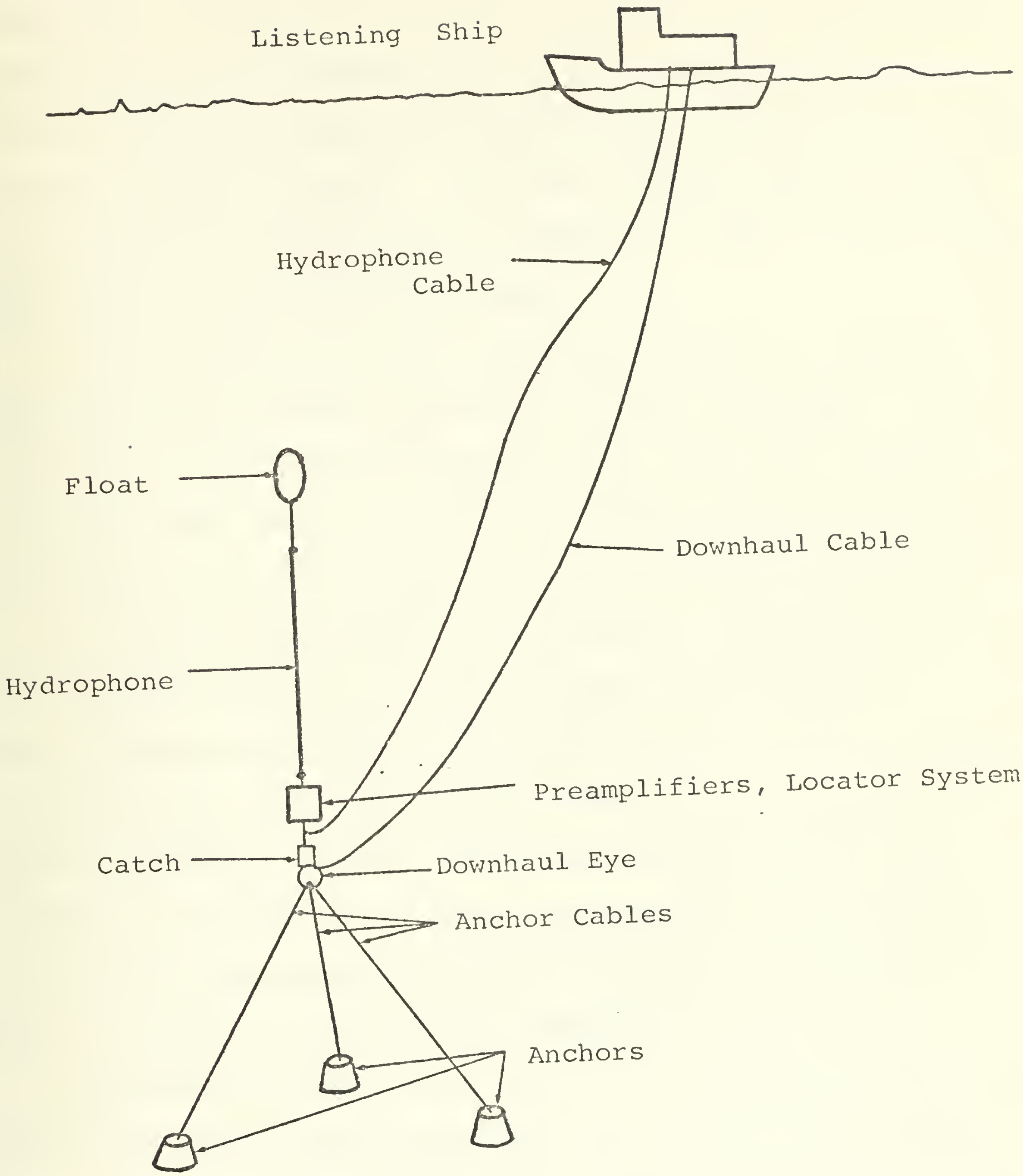

Fig. 4.3 Anchoring System for Vertical Hydrophone Array. The catch attaches the array to the anchors so that no strain is taken on downhaul cable during measurements. This allows hydrophone array to be free of surface motion effects.

ship when hydrophone retrieval is desired. During acoustic measurements the buoyant force of the hydrophone float is completely counteracted by tension in the anchor cables. The downhaul cable is slack. This method should free the array from any surface wave induced movement as well as avoid movement due to near surface currents.

Another technique which might prove useful in minimizing the hydrophone movement would be to use a vertically stable platform to mount the hydrophone such as the FLIP research vehicle. This vehicle or ones of similar design provide a very deep vertical platform which is relatively insensitive, in the vertical direction, to wave motion. The advantage of this type of platform on which to mount the hydrophone is that it can be utilized in very deep water, can serve as the listening ship and eliminates the problems associated with bottom placed equipment. The disadvantages of this type of platform are expense, manpower requirements, positioning of the vehicle and submarine Commanding Officer's aversion to passing close to a hard, large submerged object.

Regardless of the method used to fix the hydrophone, care must be taken to ensure that the CPA is not so close as to place the hydrophone within the turbulent boundary layer of the ship or its wake. To do this would result in the hydrophone recording turbulent pressure as well as acoustic pressure.

V. APPLICATION OF PLANE MODEL IN SUBMARINE ACOUSTIC MEASUREMENTS

Conducting measurements of submarine radiated noise using the plane model could be done without an acoustic range. However, because many other tests for submarines are performed using instrumented acoustic ranges, it would be logical to make the near-field measurement at the same time and utilize the acoustic range facilities. Discussed below are some procedure and technique concepts by which the near-field measurements described in the preceding sections could be taken utilizing acoustic range facilities.

A. RANGE PREPARATIONS FOR MEASUREMENTS

The acoustic range should be in operation at least in the specific area where the measurements are to be made. The listening ship and the submarine should be fitted with range tracking transducers. The locator system for the line hydrophone (See Fig. 4.3) should also have a tracking transducer, activated from the listening ship, to fix the location of the hydrophone. The listening ship should emplace the line hydrophone and monitor the line hydrophone for ambient noise before the submarine gets on the range. Once the hydrophone is in place as shown in Fig. 4.3 and the equipment operation checked satisfactorily, the listening ship records the submarine radiated noise as directed by the range coordinator. The data acquisition from this point on follows the same procedures and restrictions that exist for taking underway

radiated noise surveys as described generally in Ship Acoustical Surveys, NAVSHIPS 0900-004-3000. The data from the line hydrophone is recorded on one channel of a multi-channel recorder. Other channels are utilized to record time data, voice comments by the listening ship, position data (if not recorded by range tracking system) and such other signals as may be needed for the equipment or desired by the activity conducting the survey.

B. SUBMARINE PREPARATIONS AND NAVIGATION

A tracking transducer and a tonal transducer should be installed on the submarine. The tonal transducer should be located at the keel near the engineering spaces and the tracking transducer located at the position desired by the range facility. In addition to these transducers an Acoustic Range Measuring System (ARMS) or equivalent system should be installed on the submarine for its navigational use. This system utilizes synchronized clocks and an acoustic pulse for range determination. At a specified time the master clock on the listening ship triggers an acoustic pulse from a transducer in the locator system below the array. The time of the arrival of the pulse at the submarine is detected by the ARMS hydrophone and compared, in time, on the slave system on the submarine. The time difference is displayed as range in yards. This system would give the immediate range information required by the submarine to achieve a small closest point of approach (CPA) to the hydrophone. Other position information from the acoustic range tracking system could be

given to the submarine via the underwater telephone. This position information would be utilized to line the submarine up on the proper track to achieve the desired CPA to the hydrophone. A small CPA is a critical requirement for effective use of the near-field measurement technique. If the CPA is not small, then the size of the plane over which the acoustic pressure must be integrated would have to be increased. This would also increase the significance of multipath contribution to the measured acoustic pressure. For both reasons it is clear that a small CPA is a necessity. This means that the activity making the measurement and the submarine must both devote sufficient attention to accurate submarine navigation on the range to ensure that a CPA of ten to twenty meters can be achieved.

C. ACOUSTIC DATA ANALYSIS

Once the acoustic data have been recorded on the magnetic tape, it is ready for reduction and analysis. The first step in analyzing the data is to correct it for Doppler effects. Two techniques for such corrections are discussed in Section IV and will not be presented here again. Following Doppler correction by one of these techniques the recorded signal must be broad and narrowband analyzed to determine what discrete frequencies are significant and for which beam patterns should be calculated. Once this has been decided, the processing of the signal for a tonal beam pattern may be done. To do this we need to generate the complex pressure function, p(x), to solve the equation:

$$p(P) = \frac{-jk}{4\pi r_0} e^{jkr_0} (1+\cos\Theta) \int_{-w/2}^{w/2} p(x)\, e^{-j2\pi sx}\, dx. \qquad (2.10)$$

This equation, repeated from Section II, is the working formula needed to obtain the pressure at a point, P, in the far-field.

A possible technique for obtaining p(x) from the Doppler corrected acoustic data is illustrated on Fig. 5.1. Here the acoustic data is narrow-band filtered to obtain the desired discrete frequency, f_p. The desired frequency is also generated by the stable local oscillator shown, to serve as a stable phase reference. The acoustic signal is compared to the phase reference signal to generate a relative pressure phase by a phase analyzer. The relative phase dc signal output from the phase analyzer is input to an analog/digital converter. The amplitude is measured by a VTVM or equivalent instrument which outputs a dc signal proportional to amplitude to the analog/digital converter. The digital output of the analog/digital converter represents the complex pressure as a function of time. However, since the ship velocity and Doppler corrections applied are known, the complex pressure as a function of horizontal position, x, can be easily calculated.

The use of the generated function, p(x), in determining a normalized far-field beam pattern has been demonstrated by the experimental work discussed in Section III. The logical sequence of processing by a computer for the complex pressure function, p(x), would be:

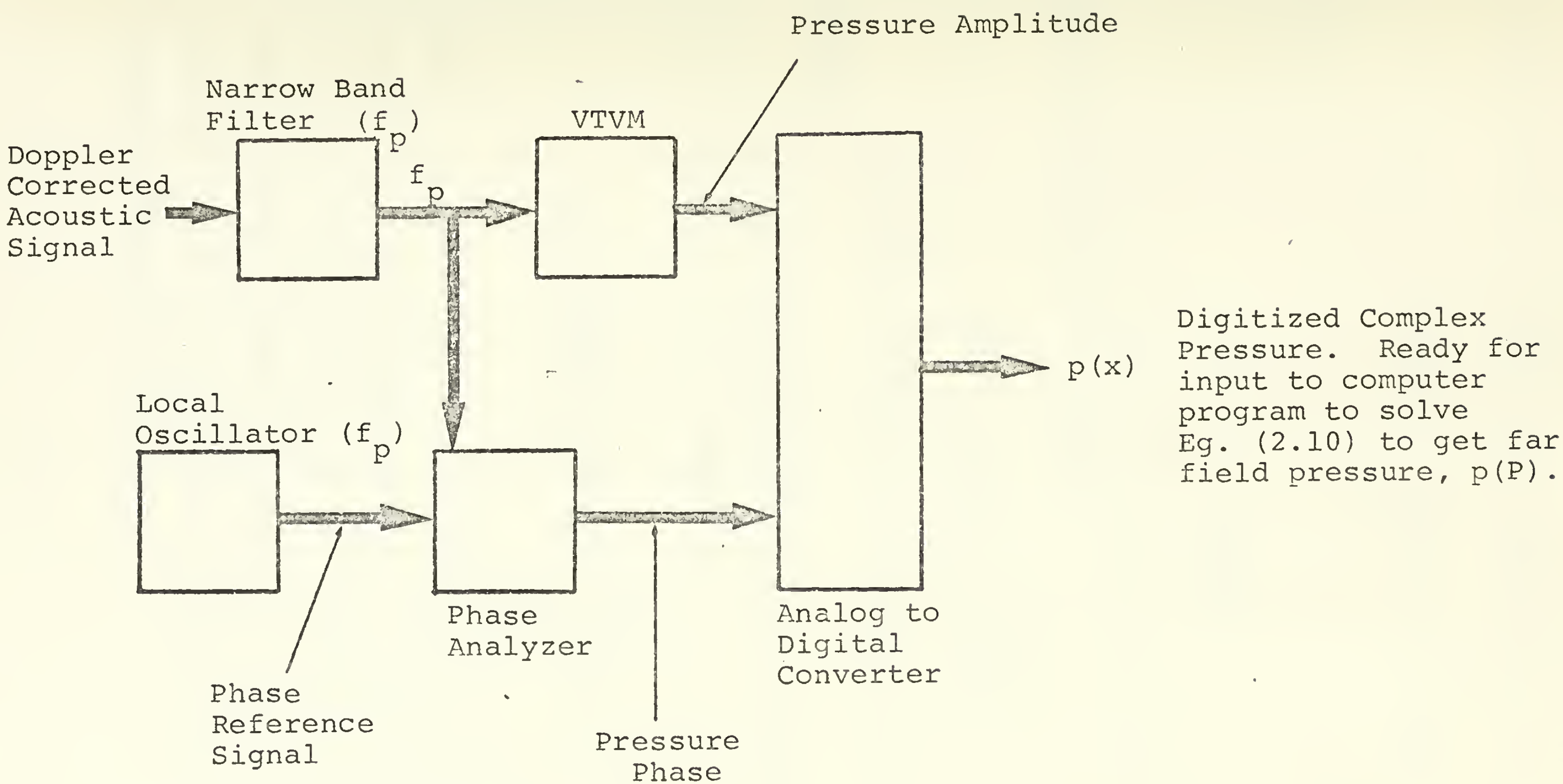

Fig. 5.1 Processing of Doppler Corrected Acoustic Signal. The acoustic speed is narrow band filtered to obtain the desired tonal and processed to output a complex pressure as a function of time. Distance, x, is velocity times time.

1. Input p(x) as a complex vector into a Fourier transform routine to perform the integration of Equation (2.10):

$$D(s) = \int_{-w/2}^{w/2} p(x)\, e^{-j2\pi sx}\, dx,$$

where

$$s = \frac{\sin\Theta}{\lambda}.$$

2. D(s) is converted to B(Θ) by substituting $s = \frac{\sin\Theta}{\lambda}$ and multiplying by (1+cosΘ):

$$B(\Theta) = (1+\cos\Theta)\; D\left(\frac{\sin\Theta}{\lambda}\right).$$

3. The beam pattern is normalized and output from the computer.

If source levels were desired in addition to a normalized beam pattern, the full equation:

$$p(P) = \left[\frac{-jk}{4\pi r_0}\right] (1+\cos\Theta) \int_{-w/2}^{w/2} p(x)\, e^{-j2\pi sx}\, dx,$$

would have to be solved for some point in the far-field at distance r_0, for a given angle Θ. This could then be used to obtain source level and the relative source levels for any angle could be determined with the beam pattern. This same technique would be repeated for each tonal of interest in the recorded submarine signature.

VI. CONCLUSION

This paper has demonstrated the possibility of obtaining far-field beam patterns and source levels for discrete frequencies radiated from a submarine by taking near-field complex pressure measurements. Although the model was developed in theory (Section II) and experimental work done to validate the model (Section III), more work needs to be done in both areas. In the theoretical model development each assumption needs to be experimentally tested for validity and modifications to the theory made if the assumptions are not approximately correct. Different configurations of sources need to be experimentally tested using the plane model and line microphones to insure that the results obtained in Section III were not a result of the configuration of the source. Actual measurements in anechoic tanks need to be made with line hydrophones to validate the estimates on the adequacy of the model for measurements with regard to surface reflections. Finally, of course, measurements of actual submarine radiated noise need to be made and compared, where possible, with actual far-field data collected by other methods.

It is important to remember that the theoretical development described in Section II imposes restrictions on the nature of the radiated noise which can be analyzed. The most important of these is that the source is a discrete frequency or can be Fourier decomposed to discrete frequencies. This restriction in the model development allows application of

the technique proposed in this paper only to stable discrete frequencies within the signature of the ship. Since the acoustic signatures of submarines contain considerable broadband noise, it would be useful to have a method similar to the one developed here to predict far-field information on narrow bands of that radiated energy. It might be possible to modify the theory developed here to be able to handle narrow frequency bands of broadband radiated noise. This paper has not addressed this problem.

The technique developed here might also be useful in measuring target strength of submarines for active sonars. The target strength is an important number in the evaluation of a ship's detectability when using the active sonar equation. Since target strength is based on the reflected echo measured in the far field, a near-field measurement technique similar to the one described in this paper might be useful in making the measurement of actual target strength.

This thesis does not purport to solve all the problems of taking submarine radiated noise measurements. Rather, it proposes a technique of measurement and analysis which could be a useful tool in evaluating a U. S. submarine's radiated noise.

APPENDIX A

COMPUTER PROGRAM FOR PROCESSING NEAR-FIELD COMPLEX PRESSURES USING THE PLANE MODEL OF SECTION II

```
C          MAIN PROGRAM

      DIMENSION WK(3029),IWK(3029),LL(3029),R(41),U(41),
     1AM(499),X(181),Y(181),DM(41),DA(41)
      COMPLEX*8 A(499),B(21)
      COMPLEX*8 CSUM
      DATA A/499*(0.0,0.0)/,N/499/

C     READ IN VALUES OF THE COMPLEX  MAGNITUDE AND PHASE
C    AND CONVERT TO REAL AND IMAGINARY PARTS

    5 FORMAT (F4.2,F6.2)
      DO 10 I=1,41
      DLM=0.0
      DLA=0.0
      R(I)=0.0
      U(I)=0.0
      DO 7 K=1,7
      READ (5,5) DLM,DLA
      RL=DLM*COS(DLA)
      UL=DLM*SIN(DLA)
      R(I)=R(I)+RL
      U(I)=U(I)+UL
    7 CONTINUE
   10 CONTINUE

C    SET UP THE COMPLEX A MATRIX

      DO 25 I=1,21
      A(I)=CMPLX (R(I),U(I))
   25 CONTINUE
      DO 35 I=480,499
      K=I-458
      A(I)=CMPLX (R(K),U(K))
   35 CONTINUE

C          COMPUTE THE FOURIER TRANSFORM FOR THE A MATRIX

      CALL FFTP(A,N,IWK,WK,LL)

C      OUTPUT THE FOURIER TRANSFORM COMPLEX VECTOR MAGNITUDE

      DO 70 I=1,499
      AM(I)=CABS(A(I))
   70 CONTINUE
   80 FORMAT ('        FOURIER MAGNITUDES')
   90 FORMAT ('0  N',8X,'MAGNITUDES')
   95 FORMAT (I4,E20.7)
      WRITE (6,80)
      WRITE (6,90)
```

```
      DO 97 I=1,499
      WRITE (6,95) I,AM(I)
   97 CONTINUE

C         WAVELENGTH OF SOUND IN CM

      W=6.9


C     SPACING OF INPUT POINTS IN HOROZONTAL DIRECTION IN CM

      D=1.25
      PI=3.141593
      DO 105 I=1,91
      C=I-1
      K=I+90
      X(K)=(180./PI)*ARSIN((C*W)/(N*D))*(-1.)
      Y(K)=(AM(I)/AM(1))*50.*(1.+COS(PI*X(K)/180.))
  105 CONTINUE
      DO 110 I=410,499
      K=I-318
      J=K-91
      C=I-500
      X(J)=(180./PI)*ARSIN((C*W)/(N*D))*(-1.)
      Y(J)=(AM(I)/AM(1))*50.*(1.+COS(PI*X(J)/180.))
  110 CONTINUE

C     SET INPUT PARAMETERS FOR THE DRAW ROUTINE


      NPTS=181
      MC=0
      ITYPE=0
      REAL LABEL/'AMPL'/
      REAL*8 TITLE(12)/'CRAWFORD',5*'        ','FAR FIEL',
     1'D BEAM P','ATTERN -',' 5000 HZ',2*'        '/
      EXSC=30.
      YSCL=20.
      IXUP=0
      IYRT=3
      MDXAX=2
      MDYAX=2
      IWIDE=6
      IHIGH=5
      IGRID=1

C     CALL THE DRAW ROUTINE


      CALL DRAW(NPTS, X,Y,MC,ITYPE, LABEL,TITLE,EXSC,YSCL,
     1IXUP, IYRT,MDXAX, MDYAX,IWIDE,IHIGH,IGRID,LAST)
      STOP
      END
```

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c.1 Submarine radiated noise far-field beam patterns for discrete frequencies from near-field measurements.